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U.S. CODE DEVELOPMENT FOR BUILDINGS WITH ADDED DAMPING

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SUMMARY

Many applications of damping devices in both new and existing buildings have resulted from extensive development efforts. The increased usage of this technology in the USA has created a demand for design guidance and building codes to specify their use. This paper provides a summary of the code development activities leading to an Appendix in the 2003 NEHRP *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* by the Building Seismic Safety Council and currently to adoption as a new section in the ASCE 7-05 Standard *Minimum Design Loads for Buildings and Other Structures*. The ASCE 7-05 will be adopted by reference in the two model building codes used in the USA: *International Building Code (IBC)* and the *National Construction and Safety Code (NFPA 5000)*.

INTRODUCTION

In 1993, the Energy Dissipation Working Group (EDWG) of the Base Isolation Subcommittee of the Structural Engineers Association of Northern California (SEAONC) started work toward providing guidance in the design of buildings with added damping devices. The EDWG developed proposed tentative design requirements applicable to a wide range of damping device hardware and recommended a testing program to verify device performance as reported by Whittaker, et al [1]. The devices included metallic, friction, viscoelastic, and viscous energy dissipation mechanisms.

The general philosophy of the EDWG design requirements was to have the main structural members remain elastic and confine the inelastic deformations primarily to the energy dissipation devices for the Design Basis Earthquake (DBE). Furthermore, since passive energy dissipation technology was still relatively new, a conservative approach was taken on many issues. For example, an experienced independent engineering review panel to conduct a review of the energy dissipation system design and the associated prototype testing programs was mandated for all projects.

A simpler approach was included in 1994 as Appendix to Chapter 2 of *FEMA 222A NEHRP Recommended Provisions for Seismic Regulations for New Buildings* [2]. The purpose of this Appendix was to introduce potential users to these new and relevant techniques, but it was not to be considered for use as code requirements. It used an equivalent viscous damping approach for the design, but required

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nonlinear response history analyses for all systems using damping devices other than linear velocity proportional devices. It also recommended a testing program similar to that proposed by EDWG.

During this period of time a significant effort funded by the Federal Emergency Management Agency (FEMA) was underway to generate technical guidelines for the seismic upgrading of buildings. Energy dissipation systems were included among the available techniques to improve seismic performance. The results of these efforts were published in 1997 as Chapter 9 of FEMA 273 *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* [3]. This document takes a performance-based approach to system upgrades. Chapter 9 outlines linear static, linear dynamic, nonlinear static, and nonlinear dynamic procedures for energy dissipation systems in parallel with the techniques used in the other design and analysis chapters in FEMA 273. Chapter 9 also provides recommended quality control and prototype testing programs, and an independent panel for review of the system design and testing programs. This guideline was more extensive than either the EDWG guidance or the FEMA 222A approach, but it could not be referenced or quoted for the proposed FEMA 302 *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* [4] because FEMA 273 had not been published or made generally available at the time FEMA 302 went to ballot. As a result, FEMA 302 Appendix to Chapter 13 entitled "Passive Energy Dissipation Systems" only provided brief statements as to the benefits of damping for improved performance, suggested rational design procedures be used, and recommended an independent panel for design and test program review. It was recognized by all participants that this Appendix was only a placeholder for more thorough requirements to be proposed for the 2000 edition of the *NEHRP Recommended Provisions*.

In 2001 the Appendix to Chapter 13 of FEMA 368 *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* [5] was published. This Appendix is entitled "Structures with Damping Systems". It was intended to be applicable to all types of energy dissipation systems, to provide design criteria comparable to conventional design performance, to provide design criteria for enhanced seismic performance, to distinguish between the design of members that are part of the energy dissipation system and the design of members independent of that system. It permitted a static design approach when the structure and energy dissipation system satisfy configuration and other restrictive criteria. It required an independent engineering review of the design and testing programs.

In 2002 the technical content of the Appendix to Chapter 13 of FEMA 368 was reordered, and design acceptance criteria were added. The Appendix with these changes was accepted as a new chapter for the 2003 edition of the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* [6]. After this acceptance, the updated version was submitted to the American Society of Civil Engineers (ASCE) Standards Committee 7 for acceptance in the 2005 edition of the ASCE 7-02 *Minimum Design Loads for Buildings and Other Structures* [7]. ASCE 7-05 will include a general reformat as well as the technical additions as proposed. The following provides information on the content and requirements as proposed to the ASCE 7 Standards Committee without including the undecided format changes. Although much of the following text is taken from the proposal to ASCE, the section and equation numbering system have not been duplicated.

1. PROVISIONS FOR STRUCTURES WITH DAMPING SYSTEMS

In this discussion any differences in requirements between the different Seismic Use Group and Seismic Design Category classes have been ignored. The emphasis in this paper is on the technical provisions contained in the design procedures. The sequence of requirements is: General design requirements, Nonlinear procedures, Response spectrum procedure, Equivalent lateral force procedure, Damped response modification, Seismic load conditions and acceptance criteria, Design review, and Testing. The discussion in this paper will follow this sequence copying from the proposal to ASCE Standards Committee 7 as appropriate. The following definitions were used in the proposal.

Seismic Force-resisting System
That part of the structural system that has been considered in the design to provide the required resistance to the seismic forces prescribed herein.

Damping Device
A flexible structural element of the damping system that dissipates energy due to relative motion of each end of the device. Damping devices include all pins, bolts, gusset plates, brace extensions, and other components required to connect damping devices to the other elements of the structure. Damping devices may be classified as either displacement-dependent or velocity-dependent, or a combination thereof, and may be configured to act in either a linear or nonlinear manner.

Damping System
The collection of structural elements that includes all the individual damping devices, all structural elements or bracing required to transfer forces from damping devices to the base of the structure, and the structural elements required to transfer forces from damping devices to the seismic-force-resisting system.

Displacement-dependent Damping Device
The force response of a displacement-dependent damping device is primarily a function of the relative displacement, between each end of the device. The response is substantially independent of the relative velocity between each end of the device, and/or the excitation frequency.

Velocity-dependent Damping Device
The force-displacement relation for a velocity-dependent damping device is primarily a function of the relative velocity between each end of the device, and may also be a function of the relative displacement between each end of the device.

The approach for the equivalent lateral force procedure assumes that all calculations can be made without a computer or spreadsheet. To do this a number of simplifying assumptions were made. The following will summarize some of the key elements of the recommended code procedure and assumptions.

2. GENERAL DESIGN REQUIREMENTS

The structural system considers both the basic requirements of the seismic force-resisting system and the damping system. The key to this consideration is the reduction in forces carried by the seismic force-resisting system due to the contribution of the damping system while recognizing the appropriate combination of forces in the two systems. Contrary to the common perception for linear viscous damping systems where the damping forces are proportional to velocity and the primary system forces are related to displacements, the maximum combination of forces does not occur when one is at zero and the other is at a maximum. Thus, these forces must be combined in an appropriate way. The displacements of the coupled systems are compared with the code allowable displacements.

Seismic Force-resisting System
The proposal provides that the basic lateral resisting system can be designed for as little as 75% of the applicable code lateral forces subject to two framing restrictions:

The design of the seismic-force-resisting system in each direction shall satisfy the requirements of Section 7 - Seismic Load Combinations and Acceptance Criteria as given in this paper, and the following:

1. The seismic base shear used for design of the seismic-force-resisting system shall not be less than V_{min}, where V_{min} is determined as the greater of the values computed using Equations 1 and 2 as follows:

   $$V_{min} = V / B_{v+1} \quad (1)$$

   $$V_{min} = 0.75\,V \quad (2)$$

   where:

   V = seismic base shear in the direction of interest for the seismic-force resisting system without added damping

   B_{v+1} = numerical coefficient as set forth in Table 6.1 for effective damping equal to the sum of viscous damping in the fundamental mode of vibration of the structure in the direction of interest, β_{Vm} (m=1), plus inherent damping, β_I, and period of structure equal to T_1.

   Exception: The seismic base shear used for design of the seismic-force-resisting system shall not be taken as less than 1.0 V, if either of the following conditions applies:

   a. In the direction of interest, the damping system has less than two damping devices on each floor level, configured to resist torsion.

   b. The seismic-force-resisting system has plan irregularity or vertical irregularity as defined in ASCE 7-02.

2. Minimum strength requirements for elements of the seismic-force-resisting system that are also elements of the damping system or are otherwise required to resist forces from damping devices shall meet the additional requirements of Section 7 in this paper.

Damping System
Elements of the damping system shall remain elastic unless it is shown by analysis or test that inelastic response of the elements would not adversely affect damping system function.

Procedure Selection
Nonlinear procedures, linear procedures or a combination of linear and nonlinear procedures and equivalent lateral load procedures are allowed subject to certain restrictions.

3. NONLINEAR PROCEDURES

Response history analysis with nonlinear structural members and nonlinear damping devices, linear structural members with nonlinear damping devices, nonlinear structural members with linear damping devices, linear structural members with linear damping devices are all permitted without restrictions beyond those of the basic seismic force-resisting system. If the calculated force in an element of the seismic force-resisting system does not exceed 1.5 times its nominal strength, that element may be modeled as linear. A nonlinear response history is required to confirm the performance of any design where the design spectral acceleration at one second is equal to or greater than 0.6 g.

Constantinou et al. [8], Hanson and Soong [9], Scholl [10], and Whittaker et al [1] provide detailed information to implement procedures involving linear and nonlinear response history procedures. These models are intended to include the effects of changes in time and/or temperature. If seven or more accelerogram records are used for these analyses, the average response values may be used. However, if less than seven accelerogram records are used, the maximum values of the responses must be used. If the properties of the damping device are expected to change during the duration of the response history analysis, enveloped responses using upper and lower bound limits of the device properties may be used. A nonlinear static procedure (nonlinear pushover analysis) is also permitted in combination with the equivalent lateral force procedure to be described later.

4. RESPONSE SPECTRUM PROCEDURE

The response spectrum procedure is permitted provided that (1) the damping system has at least two damping devices in each story in the direction of interest configured to resist torsion, and (2) the total effective damping of the fundamental mode in the direction of interest is not greater than 35 percent of critical.

The seismic base shear calculated by the square root sum of the squares or the complete quadratic combination of modal base shear components must be equal to or greater than the minimum base shear as described in Section 2 above. The period of the fundamental mode is adjusted to account for building inelastic response, but the higher modes retain their initial elastic periods for all modal calculations. The modal response coefficients are adjusted by the appropriate reduction factors for the added damping. The procedure specifically provides for the determination of the maximum story velocities for use in design of the damping system.

5. EQUIVALENT LATERAL FORCE PROCEDURE

The equivalent lateral force procedure is permitted provided that (1) the damping system has at least two damping devices in each story in the direction of interest configured to resist torsion, (2) the total effective damping of the fundamental mode in the direction of interest is not greater than 35 percent of critical, (3) the seismic-force-resisting system does not have vertical or plan irregularities, (4) the floor diaphragms are rigid, and (5) the height of the structure above its base does not exceed 30 meters (100 feet). One unique concept is the introduction of the residual mode in the static equivalent lateral force procedure. The fundamental mode and the residual mode are combined in a square-root-sum-of the-squares approach for comparison with the minimum design base shear. A description of this development and verification of its accuracy are provided by Ramirez et al [11]. Specifically from the proposal:

Seismic base shear

The seismic base shear, V, of the seismic-force-resisting system in a given direction shall be determined as the combination of the two modal components, V_1 and V_R, in accordance with the following equation:

$$V = \sqrt{V_1^2 + V_R^2} \geq V_{min} \quad (3)$$

where:

V_1 = design value of the seismic base shear of the fundamental mode in a given direction of response,

V_R = design value of the seismic base shear of the residual mode in a given direction, as determined by Equation 5, and

V_{min} = minimum allowable value of base shear permitted for design of the seismic-force-resisting system of the structure in direction of the interest as discussed in Section 2.

Fundamental mode base shear
The fundamental mode base shear, V_1, shall be determined in accordance with the following equation:

$$V_1 = C_{S1}\bar{W}_1 \qquad (4)$$

where:

C_{S1} = the fundamental mode seismic response coefficient and

$\bar{W}_1$ = the effective fundamental mode gravity load including appropriate portions of the live load.

Residual mode base shear
The residual mode base shear, V_R, shall be determined in accordance with Equation 5 as follows:

$$V_R = C_{SR}\bar{W}_R \qquad (5)$$

where:

C_{SR} = the residual mode seismic response coefficient as defined in terms of the spectral response and design values, Equation 10, and the damping coefficient factor of Table 6.1, and

$\bar{W}_R$ = the effective residual mode gravity load of the structure determined by Equation 8.

Residual mode properties
The residual mode shape, φ_{iR}, participation factor, Γ_R, effective gravity load of the structure, $\bar{W}_R$, and effective period, T_R, shall be determined using Equations 6 through 9 as follows:

$$\phi_{iR} = \frac{1 - \Gamma_1\phi_{i1}}{1 - \Gamma_1} \qquad (6)$$

$$\Gamma_R = 1 - \Gamma_1 \qquad (7)$$

$$\bar{W}_R = W - \bar{W}_1 \qquad (8)$$

$$T_R = 0.4T_1 \qquad (9)$$

where:

T_1 = effective period of the fundamental mode of vibration of the structure in the direction under consideration.

Residual mode seismic response coefficient
The residual mode seismic response coefficient, C_{SR}, shall be determined in accordance with the following equation:

$$C_{SR} = \left(\frac{R}{C_d}\right)\frac{S_{DS}}{\Omega_0 B_R} \qquad (10)$$

where:

B_R = Numerical coefficient as set forth in Table 6.1 for effective damping equal to β_R, and period of the structure equal to T_R.

Although used in each step of the process, the primary purpose of the residual mode is to provide a better estimate of the maximum interstory relative velocities for estimating the maximum forces in the viscous damping devices and their supporting members.

6. DAMPED RESPONSE MODIFICATION.

The effective damping coefficient for the building is established as a combination of the inherent damping of the structural system, the damping added by installed damping devices and nonlinear hysteretic structural energy dissipation. The equation for this effective damping from the proposal without the subscripts for design or maximum earthquake level considered is

$$\beta_m = \beta_I + \beta_{Vm} \sqrt{\mu} + \beta_H \tag{11}$$

where β_m is the effective damping in mode m, β_I is the inherent damping of the structural system, $\beta_{Vm} \sqrt{\mu}$ is the equivalent viscous damping of the supplemental damping system in mode m, and β_H is the hysteretic damping of the structural system. This effective damping modifies the structural response by coefficients as given in Table 6.1. The ductility, μ, is a key parameter in both the modal viscous damping and the hysteretic damping terms. In general, the determination of the actual ductility is an iterative process. It starts with an estimate of the displacements or ductilities, establishes a preliminary design, calculates the resulting displacements, compares the assumed and calculated displacements, and then iterates as needed. The proposal provides for the maximum ductility that can be assumed for a standard seismic force-resisting system based on its design properties. This provides an upper limit for the preliminary design.

Inherent Damping
The inherent damping is based on the structural material type, and shall not be taken greater than 5% of critical unless justified by test data or analysis.

Hysteretic Damping
This only includes inelastic, hysteretic deformations of the seismic force-resisting system. It does not include hysteretic deformations of the damping devices, which is included as equivalent viscous damping up to the point when the seismic force-resisting system yields. The calculation of hysteretic damping of the seismic force-resisting system and elements of the damping system shall consider pinching and other effects that reduce the area of the hysteresis loop during repeated cycles of earthquake demand. The hysteresis loop adjustment factor, q_H, is defined as 67 percent of the ratio of the period where the design spectra changes from acceleration dependent to velocity dependent and the fundamental period of the building. The q_H factor shall not be taken as greater than one, nor it need not be taken as less than 0.5. Unless analysis or test data supports other values, the hysteretic damping of higher modes of vibration in the direction of interest shall be taken as zero. For the design level earthquake, D, the proposed equation is

$$\beta_{HD} = q_H \left(0.64 - \beta_I\right)\left(1 - \frac{1}{\mu_D}\right) \tag{12}$$

Viscous Damping
All energy dissipated by damping devices is included in this term. For displacement-dependent devices, only the hysteresis area at displacements less than or equal to the structural yield displacement is included in this calculation. This assumes that the hysteretic device energy dissipation after the structure begins yielding is so small relative to the energy dissipation of the structure itself that it can be neglected in determination of the total energy dissipation.

Table 6.1
Damping Coefficient, B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD}, or B_{mM}

Effective Damping, β (percentage of critical)	B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD} or B_{mM} (where period of the structure $\geq T_0$)
≤ 2	0.8
5	1.0
10	1.2
20	1.5
30	1.8
40	2.1
50	2.4
60	2.7
70	3.0
80	3.3
90	3.6
≥ 100	4.0

T_0 is equal to 0.2 times the transition period between constant spectral acceleration and constant spectral velocity. The intent is that these factors should not be used for extremely short period building responses.

7. SEISMIC LOAD CONDITIONS AND ACCEPTANCE CRITERIA

The seismic load conditions and combination of modal responses for the equivalent lateral force procedure and the response spectrum procedure require the consideration of three cases. They are (1) the stage of maximum displacement, (2) the stage of maximum velocity, and (3) the stage of maximum acceleration. Force coefficients are given to account for different damper velocity exponents varying from 0.25 to 1.0 and for ductilities from less than 1.0 to 2.2 and greater. For response history procedures the maximum element forces are calculated directly and compared with appropriate allowable material values.

8. DESIGN REVIEW

A design review of the damping system and related test programs shall be performed by an independent team of registered design professionals in the appropriate disciplines and others experienced in seismic analysis methods and the theory of energy dissipation methods.

The design review shall include, but need not be limited to, the following:

1. Review of site-specific seismic criteria including the development of the site-specific spectra and ground motion histories and all other design criteria developed specifically for the project;
2. Review of the preliminary design of the seismic-force-resisting system and the damping system, including design parameters of damping devices;
3. Review of the final design of the seismic-force-resisting system and the damping system and all supporting analyses; and
4. Review of damping device test requirements, device manufacturing quality control and assurance, and scheduled maintenance and inspection requirements.

9. TESTING

The proposal requires that at least two full-size damping devices of each type and size used in the design be tested. Reduced-scale prototype devices can be used to qualify the rate-dependent properties if they are of the same type and materials, manufactured by the same processes, and tested at a similitude-scaled frequency that simulates the full-scale loading rates. At least 2000 continuous fully reversed cycles at the fundamental period and device amplitude expected in the design windstorm are required. At least five fully reversed, sinusoidal cycles at the maximum earthquake device displacement and response frequency are required. If the devices have characteristics that vary with temperature, tests at a minimum of three temperatures covering the operating range of the expected temperatures shall be used. A production test program should be established to ensure that the installed devices have the force-velocity-displacement characteristics that fall within the design limits.

Acceptance criteria are specified separately for displacement-dependent damping devices and velocity-dependent damping devices.

CONCLUSION

Perhaps the most common complaint about the approach given in *FEMA 368* Appendix to Chapter 13 and as proposed for ASCE 7-05 is that it appears too complex and mathematical. These approaches have been thoroughly tested for the conditions within the stated limits with remarkable success. What appears to be complex on first reading becomes a path to follow in implementing these techniques. The equivalent lateral force procedure has been programmed on a spreadsheet to illustrate its ease in application. Comparisons of the spreadsheet results with corresponding response history results have demonstrated the reliability of the procedure. However, many design firms prefer to use a response history calculation as final verification of the combined system performance. In that case, any reasonable method for preliminary design of the seismic force-resisting system and the damping system can be used. Although the purpose of this paper was not to extol the benefits of adding a damping system to a traditional lateral force resisting system, the benefits of doing so are clear.

It is anticipated by the authors that ASCE 7 will accept this proposal and that, in turn, ASCE 7-05 will be adopted by the two model building codes in the USA, which are the International Building Code and the NFPA 5000 - Building Construction and Safety Code.

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